Climate Impacts of LCLU Changes on a Tropical Coastal Region under a Changing Climate

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ABSTRACT

Quantification of total climate changes due to the combined effects of land cover and land use (LCLU) and green house gases (GHG) is becoming essential. This research has the high level goal of improving our understanding of these combined climate effects (LCLU + GHG) in tropical coastal areas, taking Puerto Rico as testing case. The research uses an integrated approach of high-resolution remote sensing and climatological data, linked to a numerical atmospheric model (RAMS) employed to perform ensembles of climate simulations (combining 2-LCLU and 2-global climate scenarios). Reconstructed agricultural maps (1951 & 2000) are used to define past and present LCLU, complementing the present with remote sensing data. Direct and cross comparison of the results is allowing quantifying single, combined, and competitive effects. Results indicate that global GHG have dominant effects on minimum temperatures (following regional tendencies), while urban sprawl dominates maximum temperatures. Forestation of past agricultural areas has an overwhelmingly mitigation effect on temperatures.

Introduction

Human activity in urban environments has impacts in the regional scale including changing the atmospheric composition, affecting the water cycle, and modifying ecosystems. Nevertheless, our understanding of the role of urbanization in the eco-climate system is incomplete, yet it is critical to determine how the coastal environment's atmosphere-ocean-land components act reciprocally in a connected system. The most clear mesoscale indicator of climate changes due to urbanization is a well-known urban/rural convective circulation known as urban heat islands (UHI). UHI effects of diverse magnitudes have been reported for a number of cities (Landsberg, 1981; Jauregui, 1997; Noto, 1996; Dixon and Mote, 2003; Shepherd, 2005). The majority of these previous studies focus on large continental cities, generally located in temperate northern latitudes, and although the general pattern is very similar, each city is exposed to diverse local and synoptic factors, which causes the study of UHI to be complex and specific of the locality.

Tropical coastal areas represent an interesting case in which global, regional and local effects converge thru general atmospheric circulations, large urban centers, and pristine rain forests, and compose a major part of the global biodiversity hotspots which require focused attention (Myers et al. 2000). However, studies of LCLU changes in these tropical locations and its associated climate impacts have been very limited. UHIs in tropical regions have been identified in Kuala Lumpur, Malaysia, the island state of Singapore (Tso, 1996), and in the San Juan Metropolitan Area (SJMA), Puerto Rico (Velazquez-Lozada et al. 2006), by comparing historical temperature differences between urban centers and their rural surroundings, followed

by numerical simulations. In the SJMA large UHI values were found during the Caribbean Dry and Early Rainfall Seasons (DS and ERS respectively), which together comprise the period from December to June, when dry and calm conditions prevail over the region. The ATLAS Mission, an extensive experimental campaign, was then conducted in the SJMA during the DS of 2004 (González et al. 2006).

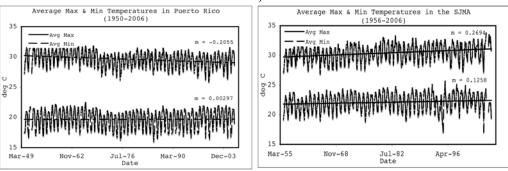
LCLU change studies not related to urbanization have also been conducted in Central America (Ray et al. 2006) and Puerto Rico (Van der Molen et al. 2006), focusing primarily on the effects of deforestation, agriculture, and natural coverage of abandon agricultural lands (either by pasture, shrubs or forest). A conclusion drawn from these LCLU studies is that local, regional, and global influences may produce net competing effects (e.g. increased humidity vs. drying, cooling vs. heating) not investigated together before.

The rapidly changing global climate and environment adds complexities to the studies of LCLU change in tropical coastal regions, particularly in the case of the Caribbean Basin, which is a region highly susceptible to large-scale multi-decadal oscillations and is among the most seriously impacted regions in the world by global climate changes (Angeles et al. 2007). Historical temperature trends in Puerto Rico based on station data are showing some of these impacts as reflected in increasing daily minimum temperatures and decreasing daily maximum temperatures (Duchon, 1986; CDC data). The increasing trend of both daily maximum and minimum temperatures in a station located in the San Juan Airport might be due to sprawling urbanization and the expansion of the local UHI, but it does not account for the asymmetric trend in daytime and nighttime temperatures observed at other locations. Any comprehensive study of the impacts of LCLU changes in tropical coastal regions under conditions of global warming, should include a detailed analysis of the contribution of each of these factors individually and as a combination of them. The overall goal of the present research is to gain a better understanding of these impacts, taking the northeastern region of Puerto Rico as the testing case. Here the factors referred to converge with the interaction of the Atlantic Ocean and coastline, the SJMA, the Central Mountains, and the Luquillo Experimental Forest (LEF), a tropical montane cloud forest.

Climate Change and LCLU Changes in Puerto Rico

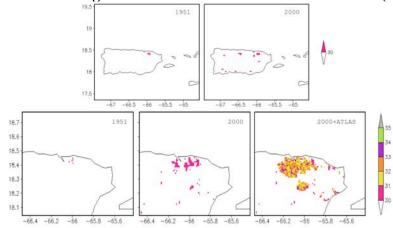
The premise and hypothesis of this project is supported by evidence of global climate change reflected in different ways in the Caribbean Basin and by dramatic changes in vegetation classes and urbanization observed for the island of Puerto Rico. Climate change manifests mainly in the form of changes in averaged global temperatures, much of this change caused by the increase of global concentrations of atmospheric green house gases, their increased release in turn attributed to human activities. The Caribbean Basin has been reported as a region especially susceptible to global climate change where changes in monthly averaged maximum and minimum temperatures recorded by a selection of Co-operative (COOP) stations follow an interesting pattern of decreasing maximums and increasing minimums (Figure 1a). When focusing on the stations located within the current limits of the SJMA, it is shown that not only averaged minimum temperatures increase with a more pronounced slope, but also that maximum temperatures have increased at a high rate as indicated by the large positive slope (Figure 1b).

Figure 1. Monthly Averaged Maximum and Minimum Temperatures in the Island of Puerto Rico and the SJMA, for the Period 1956-2006



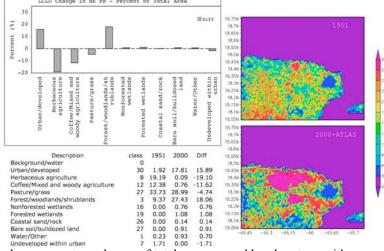
Puerto Rico (left panel), SJMA (right panel). Slopes (m) in both panels and all trends have units of °C/10yr. Data obtained from the COOP station network located throughout Puerto Rico and archived by the Southeast Regional Climate Center

Figure 2. Urban Change in Puerto Rico for a Period of 50 Years (1951-2000)



Puerto Rico (top panels) and northeastern Puerto Rico (bottom panels)

Figure 3. LCLU Change in Northeastern Puerto Rico for a Period of 50 Years (1951-2000)



Left-hand side panels show percentage change of total area covered by class type with conversion rates; right-hand side panels show the LCLU maps used to define the surface characteristics of each timeframe (1951, top; 2000, bottom)

This inversion in the maximum temperature slope in the SJMA might be linked to an advanced increase in urbanized area in northeastern Puerto Rico, an increase of approximately 16% of the total area of study and 9% of the total island area from 1951 to 2000, and the sprawl of the SJMA with its expanding limits during the last 50 years (see Figures 2 & 3). An analysis of eleven (11) land classes represented in the digital LCLU maps, background water (or ocean) was not included, shows that the main conversions of land classes was from a more agricultural scenario in the 1951 map to a heavily urbanized, forested, and shrubland covered landscape in 2000 (Figure 3). These changes are bound to have a profound impact in the region's meteorology as shown by previous studies (Van der Molen et al. 2006, Velazquez-Lozada et al 2006, Comarazamy et al. 2009), and possibly its climatology in the long term. The main objective of this research is to quantitatively assess these long-term climate effects of these changes.

Methodology and Configuration

In order to achieve the research goals, an ensemble of numerical atmospheric model simulations was performed in an attempt to separate the signals expressed in the previous sections. The model chosen for the study is the Regional Atmospheric Modeling System (RAMS), a highly versatile numerical code developed at Colorado State University to simulate and forecast meteorological phenomena (Pielke et al. 1992; Cotton et al. 2003).

General Model Configuration

The simulations focus on the northeastern coast of Puerto Rico, with especial interest in the SJMA and the LEF, and were conducted with three nested grids. Grid 1 covers great part of the Caribbean basin with a horizontal resolution of 25 kilometers. Grid 2, which is nested within grid 1, covers the island of Puerto Rico with a horizontal resolution of 5 kilometers. Grid 3 is nested within grid 2, centered in the city of San Juan with a resolution of 1km, and covers the SJMA, the complete LEF east of San Juan (also referred to as El Yunque), the relatively non-developed regions west and south of the city, and ocean space to the north (Figure 4). The vertical grid structure consists of a grid spacing of 30 meters near the surface and stretched at a constant ratio until a Δz of 1000m is reached. All the runs performed span the 3-month ERS, from April to June. This is part of the time of the year most convenient to study UHI effects, and represents the end of the Dry Season and the onset of the Mid-Summer Drought (Magaña et al. 1999), a critical period in the annual hydrological cycle of the island and during which the atmospheric model has performed satisfactorily (Comarazamy and González, 2008).

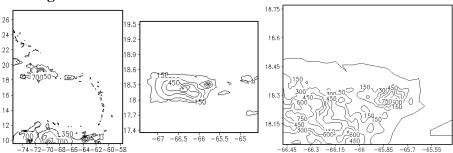


Figure 4. Model Grids used in the Numerical Simulations

Topography contours have an interval of 350m in top left panel, and 150m in top right and bottom panels

LCLU Specifications

As part of the proposed methodology, the research uses an integrated approach of analyzing information from remote sensors and other observational data, and linking them with RAMS to perform the ERS simulations in the area of interest. RAMS has been coupled with data from the Airborne Thermal and Land Applications Sensor (ATLAS) and with GIS-type LCLU maps, to update the model's surface characteristics (term RAMS+ATLAS herein) at 5km and 1km horizontal grid resolutions. The RAMS+ATLAS set-up has been validated with ground sensors and weather stations and tested separately for the region (Comarazamy et al. 2009). The land use configuration for this research consists of two scenarios: the current conditions are provided by digitalized maps of LCLU for 2000 supported by the mentioned remote sensing data of the SJMA obtained during the winter of 2004; and the past conditions are represented by digitalized maps of LCLU for 1951 (see Figure 3, right panels, for each representation). The research focuses on the impact that these land use scenarios, combined with large-scale atmospheric data for each of the two time periods (i.e. 2000 and 1955), may have on temperature and precipitation. The year of 1955 was chosen to perform the past simulation, instead of 1951, to reduce the influence of large-scale global oscillations on the model results and to have compatibility between the two periods. The global concentration of green house gases is reflected in the large-scale 2.5°x2.5° atmospheric temperature, relative humidity, and horizontal wind components, used to drive the model runs. It should be clarified that the simulations for both time periods use present values of sea surface temperatures (SST). In order to have a more accurate representation of the 1955 climate a reconstructed SST dataset for the period should be used, a possibility currently under investigation. Table 1 summarizes and describes the simulations configured for the research presented in this paper.

Table 1: Simulation Matrix

| Run ID | LCLU | Driving Conditions |
|-----------|--------------|-----------------------------------|
| PRESENT1* | 2000 + ATLAS | Present Clim. & GHG concentration |
| PRESENT2 | 2000 + ATLAS | Past Clim. & GHG concentration |
| PAST1 | 1951 | Present Clim. & GHG concentration |
| PAST2 | 1951 | Past Clim. & GHG concentration |

^{*}Serves as the control run

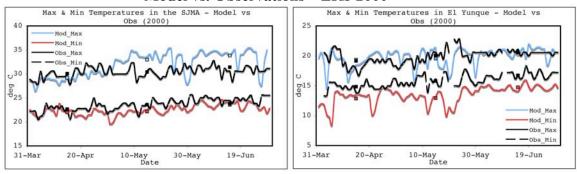
Results

Model Validation

The model results produced by the RAMS+ATLAS run for the ERS of 2000 were compared with observations from the network of COOP stations shown in Figure 1. The daily maximum and minimum temperature time series presented in Figure 5 was obtained by averaging the temperature values obtained by the stations located within the SJMA and LEF, and

compared with the averaged values predicted by the model in modeling grid points closest to such stations. This comparison shows that the model performs satisfactorily capturing the general trend and averages of the DTR extremes, even though it produced slightly higher daytime highs (specially over the SJMA) and slightly lower overnight lows (specially over the LEF) than the observed values, a known bias of mesoscale model predicted daily temperature cycle and a pattern previously shown with the same model in the same area of study (Comarazamy et al. 2009).

Figure 5. Comparison of Daily Averaged Maximum and Minimum Temperatures, Model vs. Observations – ERS 2000



SJMA (left panel), LEF (right panel). Squares represent the monthly average of each variable

Impact of LCLU Changes and Global Climate Change

To study the impact of LCLU changes in northeastern PR, a comparison of air temperatures at two meters above ground level (AGL) for the scenarios simulated is performed. The analysis consists of calculating the difference between the averaged temperatures at 1200 AST (local time). The results of air temperatures averaged in mid-afternoon throughout the 2000 and 1955 ERS periods, and corresponding LCLU scenarios, are shown in Figure 6. Here it is shown that the atmospheric model predicts that the Present LCLU has an impact in the low atmosphere of the region of study. This temperature difference occurs, with positive values of up to 3.5°C, mainly over the area covered by the SJMA, although positive changes of various magnitudes are also shown throughout the domain. It is worth noting here that the vegetation cover changes from 1951 to 2000 over the entire domain, not just over the urbanized regions as was done in previous studies. The spatial pattern of the temperature differences across the domain is also visually compared to the LCLU specification in Figure 2, it is shown that SJMA is easily identified in the temperature difference plots (Figure 6, top panels). Temperature differences are also shown for the comparison of past and present atmospheric conditions, i.e. different green house gas concentrations, with positive values of up to 2.4°C (Figure 6, bottom panels). Here the differences follow a different pattern dictated by geographic position and elevation (coastal plain, mountain ridge, montane cloud forest) and not so much by land cover. An interesting pattern in Figure 6 is that temperature differences due to LCLU changes over the SJMA appear to be enhanced when driving the model with 1955 atmospheric conditions. On the other hand, differences due to changes in atmospheric conditions are higher and cover more area when running with the 1955 LCLU as bottom boundary. Another interesting case is presented in Figure 7, where the 'total' change distribution is dominated by the LCLU representation, a conclusion that is also validated by the relative contribution of the two factors analyzed to the total temperature differences shown (Figure 8). A more detail statistical analysis, for significance of the differences shown and for the signal separation, will most likely shed some light to the patterns observed in the horizontal distributions shown. Future work, besides the investigation of using past SST values for the 1950s simulations, also includes the analysis of heat fluxes and moisture dynamics to help explain the temperature differences observed.

PRESENT1 - PRESENT2

PAST1 - PAST2

Figure 6. Spatial distribution of the air temperature differences between the LCLU and Climate scenarios simulated for the study

All panels represent differences in temperatures (°C) at 2m AGL. Top panels represent differences due to changes in the LCLU specification keeping the atmospheric conditions constant (left: 2000, right: 1955); bottom panels represent differences due to the changing atmospheric conditions while keeping the LCLU specifications constant (left: present specifications, right: past specifications)

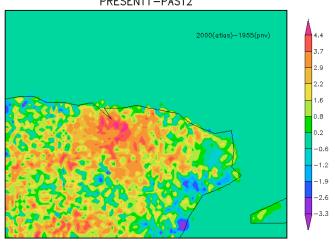
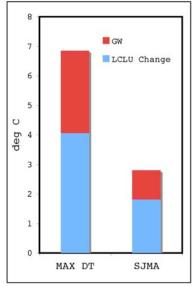


Figure 7. Spatial distribution of the 'total' air temperature difference PRESENT1-PAST2

Temperatures (°C) are at 2m AGL, and represent the difference between the simulations combining Present LCLU and atmospheric conditions, and Past LCLU and atmospheric conditions

Figure 8. Relative contribution of LCLU changes and Global Warming to the 'total' air temperature difference



Temperatures (°C) are at 2m AGL. Left hand bar represent the relative contribution to the total difference at the location were the maximum temperature differences were found; right hand bar represent the relative contribution of the two factors averaged in the SJMA region

Summary and Conclusions

A long-term data analysis of near-surface air temperatures from a network of weather stations located throughout Puerto Rico revealed that daytime maximum temperatures have a decreasing trend, and overnight minimum temperatures are increasing with time; a known reflection of global climate change in the Caribbean islands and other sub-tropical coastal regions. A close look at the stations located in and around the SJMA, however, showed that both maximum and minimum temperatures are on the rise over heavily urbanized areas, historical LCLU maps, population dynamics, and census data, led to the conclusion that this particular trend might be due to the growth of the SJMA and the conversion of natural vegetation to urban centers. In order to test this hypothesis, and quantify the relative effects of LCLU changes and global warming, a set of regional atmospheric simulations were design combining two LCLU scenarios in Puerto Rico and their corresponding atmospheric climatology (1951 & 2000, respectively). The model configuration was validated satisfactorily by comparing the results of the control run (PRESENT1, which combines 2000 LCLU & climatology) with the values recorded by the COOP stations. Model results show that there is indeed a combined effect, in terms of temperature differences (DT) in northeastern Puerto Rico, due to LCLU changes and global warming. The results for the horizontal distribution of "total" temperature changes tend to indicate that the influence of LCLU changes dominates over global warming effects, both in spatial pattern and magnitude of the DT values. A histogram of the influence of the two factors analyzed validates this conclusion, especially over the SJMA possibly due to enhanced UHI effects.

Future research will be aimed at analyzing other variables, with emphasis on allencompassing variables like precipitation and the primary variables that influence their variability (i.e. moisture, convection, heat fluxes, cloud formation and cloud coverage, among others). Of interest is to test several proposed mitigation strategies using the configuration flexibility that the atmospheric model and the current methodology provides.

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